the π^--p and K^--p charge-exchange reactions will also show a similar sharp peak at small momentum transfers. Of the known particles and resonances, the ρ alone is exchanged in π^--p and K^--p charge exchange.

In conclusion, the following differences of total cross sections $\sigma(\pi^+-p)-\sigma(\pi^--p)$ and $\sigma(p-p)-\sigma(n-p)$ can also be related to the ρ-meson trajectory at $t=0$.[8] At high energies the above differences should approach 0 with the energy dependence $s^{\alpha(0)-1}$. The experimental information indicates[9] that $\sigma(p-p)-\sigma(n-p)<2$ mb in the momentum range 5-25 GeV/c and $\sigma(\pi^--p)-\sigma(\pi^+-p)\approx 2$ mb in the momentum range 10-20 GeV/c. However, the experimental information on the n-p total cross section is scanty, and it is difficult to obtain $\alpha(0)$ from $\sigma(p-p)-\sigma(n-p)$. von Dardel et al.[9] obtained a value of $\alpha(0)\approx 0.3$ by fitting all of the π^+-p and π^--p data between 4.5 and 20 GeV/c with a Regge pole formula. However, the data are not inconsistent with a value of $\alpha(0)\approx 0.5$ or greater, and more experimental data are needed to determine $\alpha(0)$ accurately.[10]

I would like to thank Professor E. M. Henley for a critical reading of the manuscript. I would also like to thank Professor G. F. Chew for stimulating correspondence concerning this problem and Professor S. Drell and Mr. A. Pignotti for interesting discussions.

[1]H. Palevsky et al., Phys. Rev. Letters 9, 509 (1962).

[2]R. J. N. Phillips, Phys. Letters 4, 19 (1963).

[3]The $\rho\to N\bar{N}$ coupling constant quoted here is the value expected from the universal coupling of the ρ to the isovector current. J. J. Sakurai, in the Proceedings of the International School of Physics, Villa Monastero, Varenna, Como, Italy, 1962 (unpublished); in the Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962). M. Gell-Mann and F. Zachariasen, Phys. Rev. 124, 953 (1961).

[4]I. J. Muzinich, Phys. Rev. 130, 1571 (1963); D. Sharp and W. Wagner (to be published).

[5]The function $\mathcal{P}_\alpha(z)$ is related to the Legendre function of the second kind by $\mathcal{P}_\alpha(z)=-\tan\pi\alpha\, Q_{-\alpha-1}/\pi$. See M. Gell-Mann, in the Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962).

[6]A. O. Barut and D. Zwanziger, Phys. Rev. 128, 1959 (1962).

[7]The single-pion exchange is not included here; we assume that the ρ contribution is dominant. Since the single-pion exchange in perturbation theory gives results which are much too large at the larger angles, a Regge pole treatment of the single-pion exchange might be necessary.

[8]B. M. Udgaonkar, Phys. Rev. Letters 8, 142 (1962).

[9]G. von Dardel, D. Dekkers, R. Mermod, M. Vivargent, G. Weber, and K. Winter, Phys. Rev. Letters 8, 173 (1962). A. N. Diddens, H. Lillethun, G. Manning, A. E. Taylor, T. G. Walker, and A. M. Wetherell, Phys. Rev. Letters 9, 32 (1962). G. Cocconi, in the Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962).

[10]Although the assumption of a dominant ρ trajectory favors the larger value of $\alpha(0)$, the type of arguments given by A. Pignotti, Phys. Rev. Letters 9, 416 (1963), for the Pomeranchuk trajectory favor the smaller values of $\alpha(0)$. I am indebted to Professor G. F. Chew for bringing this point to my attention.

VECTOR MESON EXCHANGE MODEL FOR ISOBAR PRODUCTION*

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The one-pion-exchange model for inelastic processes has achieved some success in describing reactions like $p+p\to N_{3/2}^{*++}+n$ and $\pi^-+p\to\rho^-+p$.[1] There are, however, processes such as

$$\pi^++p\to N_{3/2}^{*++}+\pi^0, \quad (1a)$$

$$K^++p\to N_{3/2}^{*++}+K^0, \quad (1b)$$

$$\pi^++p\to Y_1^{*+}+K^+, \quad (1c)$$

$$K^-+p\to Y_1^{*+}+\pi^-, \quad (1d)$$

where one-π exchange or one-K exchange is forbidden but one-ρ or one-K^* exchange is allowed.[2] In this note we would like to present some specific predictions of immediate experimental interest based on the vector meson exchange model for isobar production.[3] The results we report here depend only on angular momentum and parity considerations; more detailed calculations including estimates of cross sections based on the "ρ-photon analogy" and the "broken eightfold way" will appear in a separate communication.

When a spin-one particle is exchanged in Reactions (1a)-(1d), we have a situation analogous to that of the electroproduction of a single pion,

$$e^- + p \to e^- + p + \pi^0, \tag{2}$$

where a virtual photon is exchanged. The overall matrix element can be written as

$$(p_\mu + p_\mu')\left[\left(\delta_{\mu\nu} + \frac{k_\mu k_\nu}{m_V^2}\right)(\Delta^2 + m_V^2)^{-1}\right] M_\nu$$

$$= v_\nu M_\nu (\Delta^2 + m_V^2)^{-1} \tag{3}$$

$$(\Delta^2 = |\vec{k}|^2 - k_0^2, \quad k_\mu = p_\mu - p_\mu', \quad m_V = m_\rho \text{ or } m_{K^*}),$$

where p_μ (p_μ') is the four-momentum of the incident (final "peripheral") π or K meson, and k_μ is the four-momentum of the exchanged vector meson, as shown in Fig. 1. M_ν is the matrix element of the transition current appropriate to the reaction

$$\rho^+ + p \to N_{3/2}^{*++} \to p + \pi^+ \tag{4a}$$

or

$$\bar{K}^{*0} + p \to Y_1^{*+} \to \Lambda + \pi^+. \tag{4b}$$

It is important to note that for a given Δ^2 only three out of the four components of the polarization four-vector v_μ are independent.[4]

We can make an angular momentum and parity decomposition of $v_\mu M_\mu$ in terms of ordinary polarization three-vectors as seen in the rest system of the baryon isobar. As in the electroproduction of a single pion,[5] it is convenient to use the language of multipole expansion. In addition to the usual magnetic and electric multipoles that appear in the photoproduction of a single pion, we also have a longitudinal multipole whose angular momentum and parity properties are identical with those of the electric multipole of the same order. We therefore have three independent amplitudes, in general, that can lead to an isobar of given total angular momentum and parity. It is evident from (3) that our most general polarization (three-)vector $\vec{v}$ necessarily lies in the production plane [the plane determined by $\vec{p}$ and $\vec{p}'$ of the "two-body" processes (1a)-(1d)]. For the polarization vector in the (transverse) electric and magnetic matrix elements, we use the component of $\vec{v}$ perpendicular to $\vec{k}$, namely, $\vec{v} - (\vec{v}\cdot\hat{k})\hat{k}$ where $\hat{k} = \vec{k}/|\vec{k}|$; let a unit vector along this direction be $\hat{\epsilon}_T$ (where the subscript T stands for "transverse"). In contrast, the polarization vector that appears in the longitudinal multipole must be parallel to $\hat{k}$. Note that $\hat{\epsilon}_T$, $\hat{k}$, and $\hat{n} = (\vec{p}\times\vec{p}')/|\vec{p}\times\vec{p}'|$ form a set of mutually orthogonal unit vectors in the isobar rest frame.

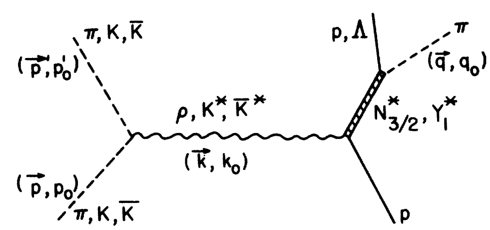

FIG. 1. Vector-meson exchange mechanism for isobar production.

Using the standard expressions for the multipole matrix elements,[5] we can easily derive the angular distribution of the "decay" pion whose momentum in the isobar rest system is denoted by $\vec{q}$. For a $p_{3/2}$ isobar such as $N_{3/2}^*$ and Y_1^*, we obtain the following decay distribution in the isobar rest frame:

$$M1 \to p_{3/2}\colon\ 1 + 3(\hat{q}\cdot\hat{n})^2, \tag{5a}$$

$$E2 \to p_{3/2}\colon\ 1 - (\hat{q}\cdot\hat{n})^2, \tag{5b}$$

$$L2 \to p_{3/2}\colon\ 1 + 3(\hat{q}\cdot\hat{k})^2. \tag{5c}$$

It is well known that the angular distribution in the photoproduction reaction

$$\gamma + p \to N_{3/2}^{*+} \to p + \pi^0 \tag{6}$$

is in excellent agreement with that expected for a pure $M1 \to p_{3/2}$ transition.[6,7] If the ρ meson is coupled to the conserved isospin current,[8,9] we expect that the matrix element for (4a) at $\Delta^2 = 0$ is proportional to that for (6),[10] just as $B^{12} \xrightarrow{\beta^-} C^{12}$, $N^{12} \xrightarrow{\beta^+} C^{12}$, and $C^{12*} \xrightarrow{\gamma} C^{12}$ have proportional matrix elements in the conserved vector current theory of weak interactions.[11] Because of this "ρ-photon analogy," it is natural to assume that the process (4a) also goes predominantly via $M1$ rather than via $E2$ and $L2$. Further, using unitary symmetry[12,13] which groups ($N_{3/2}^*, Y_1^*$), (π, K), and (ρ, K^*) into the same unitary multiplets, we may speculate that the process (4b) is also dominated by $M1 \to p_{3/2}$.

To date, the most suggestive evidence for vector meson exchange in isobar production comes from the work of Bertanza et al.[14] who observed copious production of Y_1^{*+} in Reaction (1d) at p_K(lab) $= 2.24$ BeV/c but found no trace of the reaction

$$K^- + p \to Y_1^{*-} + \pi^+, \tag{7}$$

which is strictly forbidden by the K^* exchange model. Moreover, this group reports a decay angular distribution of Y_1^* of the form

$$1+(0.5\pm 0.6)(\hat{q}\cdot\hat{n})+(4.2\pm 1.0)(\hat{q}\cdot\hat{n})^2, \qquad (8)$$

in excellent agreement with the decay distribution (5a) expected for a pure $M1 \rightarrow p_{3/2}$ transition. Once we have established the dominant $M1$ character of the $K^*-Y_1^*-N$ vertex, we can argue that the K^* exchange model requires the same decay distribution (5a) for Y_1^* in the π^+p reaction (1c) which is obtained from the K^-p reaction (1d) just by interchanging ("crossing") the incoming and outgoing "peripheral" meson lines. This expectation is fulfilled by the work of Yamamoto and collaborators[15] who observed, at $p_\pi^{(\mathrm{lab})}=2.77$ BeV/c, a Y_1^* decay distribution quite consistent with (5a). As for Reaction (1b), Kehoe[16] reports a remarkably pure $1+3(\hat{q}\cdot\hat{n})^2$ distribution (without any azimuthal anisotropy) for $N_{3/2}^*$ decay at $p_K^{(\mathrm{lab})}\approx 910$ MeV/c.

It is important to emphasize that if vector meson exchange with $M1 \rightarrow p_{3/2}$ is dominant in Reactions (1a)-(1d), then the Adair method[17] for determining the isobar spin must necessarily fail; this is because the decay distribution (5a) implies a decay distribution with respect to the "Adair direction" $\vec{p}$ (averaged over azimuthal angles) of the type $1-(3/5)(\hat{q}\cdot\hat{p})^2$ which is very different from the famous Adair distribution $1+3(\hat{q}\cdot\hat{p})^2$ expected for a spin-3/2 isobar. So, from the point of view of the vector meson exchange model, it is no surprise that the Adair method has consistently failed in determining the spins of baryon isobars.[18]

Near threshold, the production angular distribution for "two-body" reactions (1a)-(1d) must be $\sin^2\theta_{\mathrm{prod}}$ divided by the slowly varying factor $(\Delta^2+m_V^2)^2$, provided vector meson exchange with $M1 \rightarrow p_{3/2}$ dominates. (To prove this statement just note that the "magnetic field" goes like $\vec{k}\times\vec{v}\propto\vec{p}\times\vec{p}'$.) This agrees with the production angular distribution observed by Kehoe for (1b) at a total c.m. energy close to $m_K+m_{N^*}$. At higher energies, however, we do expect the usual backward peaking of the baryon isobar characteristic of the peripheral model; this expectation is in qualitative agreement with the data of references 14 and 15, but some additional Δ^2 dependence appears necessary.

At sufficiently high energies, Reactions (1a)-(1d) may be used to test the validity of unitary symmetry which relates the $K^*-N-Y_1^*$ vertex to the $\rho-N-N_{3/2}^*$ vertex, etc. In the unitary symmetry limit, we obtain[19]

$$\sigma(a):\sigma(b):\sigma(c):\sigma(d)=6:3:1:1, \qquad (9)$$

where we have assumed the now famous "tenfold way" assignment[13] for $N_{3/2}^*$ and Y_1^*. Other relations such as

$$\frac{\sigma(\pi^-+p\rightarrow N_{3/2}^{*0}+\pi^0)}{\sigma(\pi^++p\rightarrow N_{3/2}^{*++}+\pi^0)}=1/3$$

can be easily obtained from the charge independence of the $\rho-N-N_{3/2}^*$ vertex. More detailed considerations based on the "broken eightfold way" appear elsewhere.

The vector meson exchange model may be also applicable to processes like

$$K^-\,(\pi^-)+p\rightarrow Y_0^*(1520)+\pi^0\,(K^0),$$

where $Y_0^*(1520)$ is known to be a $d_{3/2}$ resonance.[20] The decay distributions analogous to (5) in the $d_{3/2}$ case turn out to be

$$E1\rightarrow d_{3/2}:\ 1+3(\hat{q}\cdot\hat{\epsilon}_T)^2,$$

$$M2\rightarrow d_{3/2}:\ 1-(\hat{q}\cdot\hat{\epsilon}_T)^2,$$

$$L1\rightarrow d_{3/2}:\ 1+3(\hat{q}\cdot\hat{k})^2. \qquad (10)$$

Finally we wish to propose a test of the one-vector-meson exchange model analogous to that given by Treiman and Yang[21] in the one-pion-exchange case. (This test is applicable regardless of the quantum numbers of the isobar produced.) Let us define the angle φ through

$$\cos\varphi=\frac{(\vec{p}\times\vec{p}')}{|\vec{p}\times\vec{p}'|}\cdot\frac{(\vec{k}\times\vec{q})}{|\vec{k}\times\vec{q}|}, \qquad (11)$$

where, as in (5) and (10), the vectors $\vec{p}$, $\vec{p}'$, $\vec{k}$, and $\vec{q}$ are to be evaluated in the isobar rest system. The isobar decay distribution for fixed $\cos\theta=\hat{k}\cdot\hat{q}$ (or the decay distribution obtained after integrating over $\cos\theta$) must be of the form

$$A+B\cos\varphi+C\cos^2\varphi, \qquad (12)$$

if one-vector-meson exchange is valid.[22] To prove this theorem we merely note that the matrix element (3) is linear in the polarization vector that can transmit information on the plane determined by $\vec{p}$ and $\vec{p}'$. Moreover, it is easy to show that the presence of the B term necessarily indicates interference with a longitudinal multipole.

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†Alfred P. Sloan Foundation Fellow.

[1]For a list of theoretical and experimental papers on the one-pion exchange model, see, e. g., E. Ferrari and F. Selleri, Suppl. Nuovo Cimento 24, 453 (1962).

[2]Throughout this paper, $N_{3/2}^*$, Y_1^*, and K^* stand, respectively, for the 3-3 resonance, the 1380-MeV π-Λ resonance, and the 885-MeV K-π resonance. The term "isobar" stands for $N_{3/2}^*$ or Y_1^*.

[3]For vector meson exchange in processes like $\pi^- + p \rightarrow K^* + \Sigma$, see G. A. Smith et al., Phys. Rev. Letters 10, 138 (1963).

[4]To prove this, just observe that $k_\mu v_\mu = 0$ for (1a) and (1b) and $k_\mu v_\mu = \pm(m_K^2 - m_\pi^2)(m_V^2 - \Delta^2)/m_V^2$ for (1c) and (1d).

[5]R. H. Dalitz and D. R. Yennie, Phys. Rev. 105, 1598 (1957).

[6]See, e. g., W. S. McDonald, V. Z. Peterson, and D. R. Corson, Phys. Rev. 107, 577 (1957).

[7]The dominance of $M1 \rightarrow p_{3/2}$ is expected on theoretical grounds: G. F. Chew and F. E. Low, Phys. Rev. 101, 1579 (1956); G. F. Chew, M. L. Goldberger, F. E. Low, and Y. Nambu, Phys. Rev. 106, 1345 (1957); S. Fubini, Y. Nambu, and V. Wataghin, Phys. Rev. 111, 329 (1958).

[8]J. J. Sakurai, Ann. Phys. (N. Y.) 11, 1 (1960).

[9]M. Gell-Mann and F. Zachariasen, Phys. Rev. 124, 953 (1961).

[10]The proportionality constant in this case is (3/2) $\times (f_\rho/e)$, where $f_\rho^2/4\pi = 4\gamma^2/4\pi \approx 2.0$, $e^2/4\pi = 1/137$. We will discuss a quantitative test of the "ρ-photon analogy" in a separate communication.

[11]M. Gell-Mann, Phys. Rev. 111, 362 (1958).

[12]M. Gell-Mann, Phys. Rev. 125, 1067 (1962); Y. Ne'eman, Nucl. Phys. 26, 222 (1961).

[13]For the unitary spin assignment of low-lying isobars, see R. E. Behrends et al., Rev. Mod. Phys. 34, 1 (1962); S. H. Glashow and J. J. Sakurai, Nuovo Cimento 25, 337 (1962); S. H. Glashow and J. J. Sakurai, Nuovo Cimento 26, 622 (1962).

[14]L. Bertanza et al., Phys. Rev. Letters 10, 176 (1963).

[15]S. S. Yamamoto (private communication).

[16]B. Kehoe, following Letter [Phys. Rev. Letters 11, 93 (1963)].

[17]R. K. Adair, Phys. Rev. 100, 1540 (1955).

[18]The Adair method is known to fail not only in (1b), (1c), and (1d), but also in (1a) [D. Stonehill, Ph. D. thesis, Yale University, 1962 (unpublished)] . On the other hand, the Adair method has been successfully applied to $N_{3/2}^*$ decay in $\pi^- + p \rightarrow N_{3/2}^{*-} + \pi^+$ [V. Alles-Borelli et al., Nuovo Cimento 14, 211 (1959)] ; note, however, that one-ρ exchange is forbidden in this reaction. It is worth remarking that at higher energies ($\sim$3.3 BeV/c), the reaction $\pi^- p \rightarrow N_{3/2}^{*-} \pi^+$ does not occur, whereas the reaction $\pi^- p \rightarrow N_{3/2}^{*-} \pi^-$ is observed [Z. G. T. Guiragossian, Phys. Rev. Letters 11, 85 (1963)] in agreement with dominant ρ exchange.

[19]The relevant Clebsch-Gordan coefficients may be found in reference 13. The relation $\sigma(a)/\sigma(b) = 2$ follows from the assumption that the ρ is coupled universally to the isospin current; the relation $\sigma(c) = \sigma(d)$ is a consequence of any model based on K^* exchange. Our relations should not be confused with Eq. (5b) of S. Meshkov, C. A. Levinson, and H. J. Lipkin [Phys. Rev. Letters 10, 361 (1963)] which follows from unitary symmetry alone.

[20]R. D. Tripp, M. B. Watson, and M. Ferro-Luzzi, Phys. Rev. Letters 8, 175 (1962).

[21]S. B. Treiman and C. N. Yang, Phys. Rev. Letters 8, 140 (1962).

[22]The Treiman-Yang distribution for the $M1 \rightarrow p_{3/2}$ case must be of the form $1 + 2\sin^2\varphi$. A correlation of this kind has been reported by S. Goldhaber et al. [Bull. Am. Phys. Soc. 8, 20 (1963); Proceedings of the Conference on Fundamental Particle Resonances, Ohio University, Athens, Ohio (to be published)] in the reaction $K^+ + p \rightarrow K^0 + N_{3/2}^{*++}$ at 1.96 BeV/c.

ISOBAR PRODUCTION BY 910-MeV/c K^+ MESONS*

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(Received 29 May 1963)

In an accompanying Letter by Stodolsky and Sakurai,[1] a model for isobar production by vector meson exchange is presented. In this Letter the predictions of that model are compared to the results of an experimental investigation of the process

$$K^+ + p \rightarrow K^0 + p + \pi^+. \tag{1}$$

The model assumes that the final-state π^+ and proton are the decay products of the $J = 3/2$, $I = 3/2$ nucleon isobar which was produced by the exchange of a ρ meson.

The events were found in a scan of 40 000 pictures from an exposure of the Berkeley 30-in. propane bubble chamber to a separated beam of K^+ mesons. The beam momentum, over the run, was distributed about 910 MeV/c with a variance of approximately 40 MeV/c. Only those events were considered which had associated with them the decay of the K^0 via the charged K_1^0 mode:

$$K_1^0 \rightarrow \pi^+ + \pi^-. \tag{2}$$

Candidates found in the scan were measured on standard digitized equipment and analyzed in the